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REA

CONCEPTUAL DESIGN OF INTEGRATED SAFEGUARDS SYSTEMS

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ABSTRACT

The Los Alamos Scientific Laboratory (LASL) is currently involved in the conceptual design of safeguards for generic facilities in the back-end of the nuclear fuel cycle (spent-fuel reprocessing, plutonium nitrate-to-oxide conversion, mixed-oxide fuel fabrication, plutonium scrap recovery, and waste handling). These studies are first steps aimed at eventually providing detailed designs of integrated safeguards systems to guide safeguards-related facility construction and/or modification. The purpose of this presentation is to describe the conceptual design process in terms of its definition, a systematic procedure for its implementation, some of the tools required, and an example of the results of a conceptual design. The value of conceptual design and its relationship to other facets of the complete facility design process are also discussed.

I. INTRODUCTION

Safeguards has historically been regarded as an adjunct to the nuclear fuel cycle, so that coordination of safeguards and nuclear materials processing has been difficult, both during design and during processing. In many cases, for example, thinking about safeguards matters related to process design has been put off to "some more suitable time." On the other side, safeguards system designers have sometimes been guilty of ignoring, or at least insufficiently considering, process economics and operational impact. These attitudes are dangerous because, as Churchman Ref. 1, p. 8 says, "... when you postpone thinking about something too long, then it may not be possible to think about it adequately at all." The point is that, for effective safeguards systems integrated with efficient nuclear material processing, safeguards and processing considerations must be coordinated from the earliest possible moment. Today's trend toward tighter regulations and increasingly stringent safeguards dictates that safeguards criteria be major factors in the selection of process and construction alternatives for new nuclear facilities. Thus, safeguards systems have evolved from the traditional role of an overlay or "retrofit" on existing processes to become an indispensable component in integrated facilities of the future.

Another common pitfall for the safeguards designer is the attempt to draw quantitative conclusions from studies of generic fuel cycle facilities. By itself, there is nothing inherently wrong with studying generic facilities and processes; this is a natural thing to do in view of the complexity of the fuel cycle and the many process options available. It is also natural to want to quantify the safeguards system and its performance, for, to paraphrase Lord Kelvin, if you can't put a number on it, you don't know it. The problem appears when the two are mixed. Useful quantitative conclusions can only be drawn from a study of a specific facility or process for which enough detail is available to address the problem adequately, and these conclusions will have to be re-evaluated for every other specific facility. Of course, generic studies can be useful for educational purposes and for developing techniques, and at some point it will be desirable to generalize on specific conclusions, but the hazards and limitations of generic studies should be recognized.

The end product of any complete system design requires a number of sequential steps that should build on one another to form a growing structure ever more detailed and practicable for satisfying the system objectives. Obviously, any step that does not add to the structure is redundant; likewise, any step that is not based on the results of previous steps is inefficient, causing doubt as to the usefulness of the whole sequence. Therefore, a careful description of the steps to be followed in design is essential. There are many ways of categorizing and naming those steps, but the following list is both minimal and informative:

1. Conceptual design,
2. Preliminary design,
3. Detailed design, and
4. System implementation.

Conceptual design, which is the major topic of this paper and is discussed in more detail in the next section, is an effort by the systems designer to scope a complex problem, <u>for his own benefit</u> as well as part of the formalized design process. Preliminary design is the first cut at converting the results of the conceptual design study into useful components of a total system. In this step, problems such as physical layout and intra-system communications are addressed, and the interactions of the components and subsystems are defined with a particular view toward implementation. Component and subsystem evaluation is usually required during this step. Detailed design provides a complete system definition, including construction specifications and operating procedures. The last step, system implementation, is included on the list because it encompasses not just system construction, but also the follow-on period during which relatively minor design changes can be made. These last three design steps will not be considered further in this paper.

II. CONCEPTUAL DESIGN

Conceptual design means different things to different people, but the meanings differ primarily in the level of detail that each would include. Fundamentally, conceptual design is the design (or selection) of concepts useful for solution of the problem at hand, and the formation from these of a larger overall solution concept. Thus, the conceptual design should be given in terms of (1) the functions that it and its subsystems must perform, and (2) an estimate of how well each function can be performed. The level of detail should be sufficient to allow at least a preliminary quantitative evaluation of the concept, and permit effective direction of design.

A conceptual design is a zeroth-order approximation to a real system that contains all the processes and controls (perhaps too many) that might be found in an idealized system designed from scratch without regard to practical constraints, such as size, complexity, and cost. Using this model, one exercises various options, hypotheses, and design concepts to determine not just what should be done, but what can be done: what the effects of parametric changes on the overall system might be, what technology is available for application now, and what technology must be developed.

After several idealized systems have been evaluated, one begins to apply the practical criteria. They are, in order of importance: feasibility, cost-effectiveness, acceptability, and convenience. Failure to satisfy the first two criteria is disqualifying. While meeting the last two may or may not be a requirement, it is certainly very desirable.

Conceptual design comprises five major steps, which may be iterated as necessary: (1) synthesis, (2) analysis, (3) evaluation, (4) modification and/or iteration, and (5) summation. This is only one way among many of partitioning the design process, but it includes all the necessary functions. More detailed discussions can be found in Refs. 1-3.

The flow chart of Fig. 1 illustrates the sequence of conceptual design steps, which are described below. Each step logically builds on previous steps, and portions of the sequence can be repeated for design refinement or improved design characterization. Clearly, if suitable definitions of the steps are made, this sequential procedure can serve as well for any of the four stages in the design cycle.

A. Synthesis

Synthesis consists of combining building blocks into an orderly structure that would appear to be capable of reaching the system goals. The phrase "would appear to be capable" is appropriate at this point, prior to the analysis and evaluation steps that would determine the system's capability.

Synthesis can be broken into five parts Ref. 1 :

1. Definition of total system objectives, specifically the performance measures for the whole system;
2. Determination of the system's environment, i.e., the fixed constraints, including such things as requirement schedules and necessary interactions with other systems;
3. Enumeration of the resources available to the system; for example, applicable technology, money, and human resources;
4. Definition of subsystem missions, that is, the functions the subsystems must fulfill to achieve the objectives of the system; and
5. Description of systems planning and operation, or how the subsystems fit together.

These five parts result in a system design that is ready for the next step, analysis. Notice that, in the early stages, the desired values of the system performance measures described under Part 1. may not be known. Thus, one of the purposes of the conceptual design step is to ascertain those values of performance measures that seem attainable.

B. Analysis

Analysis quantifies the performance of the system obtained from the synthesis step. One of the primary tools of analysis is mathematical modeling and simulation based on either deterministic or stochastic formulations. Deterministic models are useful for characterizing systems that are well known and somewhat static, or for calculating nominal or average behaviors. Stochastic (or probabilistic) models attempt to account for uncertainties in the system, e.g., unmeasurable perturbations or measurement noises, by specifying properties of the uncertainties such as the density functions. The stochastic model is then run several times, each time with different sample functions from the uncertainty distributions, to give an idea of the average system behavior and its variation about the average. This is the so-called Monte Carlo technique.

C. Evaluation

In evaluation, the results of analysis are examined to determine whether the system meets the performance goals set in the synthesis step. If the goals have been specified as "best obtainable", then a comparison with previous results is necessary.

D. Modification and/or Iteration

Depending on the outcome of the evaluation, it may be desirable to return to the synthesis step and repeat the whole process with some system modifications.

E. Summation

After steps A-D have been iterated sufficiently to give a satisfactory system conceptual design, the results are compiled and summarized in the form of a point of departure for the next part of the design cycle, preliminary design.

III. A CONCEPTUAL DESIGN EXAMPLE

Having discussed what a conceptual design means and how it might be done, consider an example of its application to safeguards. The recent Los Alamos Scientific Laboratory (LASL) and Sandia Laboratories studies [Refs. 4-5] exemplify the approach and point out some of the benefits to be gained. The following is based on the LASL report, and presumes some familiarity with the nuclear fuel cycle and safeguards.

The Westinghouse Corp. Recycle Fuels Plant (RFP) to be built at Anderson, SC, is the basis for the example. The RFP is a mixed-oxide fuel fabrication facility comprising conventional steps of feed material receipt and storage, transfer of feed to the main process stream, blending PuO_2 and UO_2 powders, powder preparation, pellet pressing, pellet sintering and grinding, and fuel rod loading, storing, and shipping [Ref. 6]. A clean scrap recovery system is also coupled to the main stream. Figure 2 shows a block diagram of the RFP processes, with typical material flows and some gross specifications.

For the purposes of this example, the major thrust of the design is directed to the problem of materials accounting. In a complete conceptual design, the interplay between materials accounting and physical protection must be considered.

A. Synthesis

The systems goals are three-fold:

1. Effective materials accounting, as measured by sensitivity to diversion;
2. Minimum operational impact, as measured by time delays in processing caused by safeguards; and
3. Minimum cost, as measured by the incremental increase in cost of the RFP.

Note that all three goals are of the "best obtainable" type, so that several versions of the system will have to be compared. Several other goals could be listed, but close examination shows that they are all subgoals under one of these three.

The system environment, or fixed constraints, includes:

1. The original RFP design,
2. The operational procedures of the RFP,
3. The limits of current technology,
4. The attitudes of the process operators toward safeguards, and
5. Regulations governing the facility.

Although 1. and 2. are listed as constraints, they are not hard constraints in that minor modifications to the RFP design and its operational procedures can be negotiated. The degree of hardness is related to how late in the design cycle safeguards criteria have been incorporated, as discussed in the Introduction.

The system's resources are numerous:

1. Modern technology, such as NDA instrumentation, conventional chemical analysis, and computerized information processing;
2. Powerful statistical techniques for data analysis;
3. Intimate knowledge of the process and its workings;
4. Past experience with safeguards systems;
5. Assistance from the physical protection system;
6. The good will of the process operators;
7. The weight of the regulatory authorities; and
8. Public opinion.

The subsystem missions for the materials accounting system comprise three parts:

1. Materials measurement: quantity and location;
2. Material balance calculations; and
3. Data analysis for diversion detection.

Systems planning and operation involve the specification of such strategies as:

1. Dividing up the process into a number of unit processes and drawing material balances for each, as well as for the entire facility. This can greatly improve sensitivity to diversion;
2. Drawing a material balance for each unit process at least once each shift (every 8 h) to give more timely, and thus more sensitive, materials accounting; and
3. The concept of graded safeguards, in which stricter accounting is applied to material of

greater strategic value. For example, PuO_2 powder is much more attractive for diversion than fuel rods.

At this point in an actual conceptual design, as in Ref. 4, the results of synthesis would contain much more detail, and would be suitable for analysis.

B. Analysis

The system must now be analyzed with regard to each of the three goals set forth under synthesis. A good tool for assessing materials accounting effectiveness is stochastic modeling and simulation of material flows and measurements. For the Westinghouse RFP study, material flows are simulated using the code MOXSIM [Refs. 4, 7], and material measurements are simulated with the code MACSIM [Refs. 4, 8], which also calculates material balances, and their associated uncertainties, for each unit process. To determine sensitivity to long-term diversion, the cusum (cumulative sum of material balances) and V-mask technique [Refs. 9-10] is applied to the MACSIM material balance data. Short-term (single-theft) diversion sensitivity is calculated by means of conventional probabilistic methods.

To illustrate the technique, consider the PuO_2 powder unloading process, in which one shipping container containing four canisters of PuO_2 powder is received each unloading shift. One canister containing $\sim$ 8 kg of PuO_2 powder is opened, sampled, and unloaded to bulk storage during a nominal 2-h period. A balance is drawn by weighing the canister contents and observing the increase in weight of the bulk storage vessel (170-kg capacity). The corresponding material balance and cusum charts for 84 shifts (4 weeks) of operation are shown in Fig. 3. The short, horizontal marks represent the material balance and cusum values, respectively, and the error bars are the $\pm$ 1σ uncertainties in these values. The wide fluctuations and sizable uncertainties in each chart are caused primarily by the uncertainty in weighing the 170-kg bulk storage vessel.

The measurement system for the PuO_2 powder unloading process (call it measurement system 1) can be implemented with equipment already designed into the RFP, so that the incremental equipment cost should be very low. In addition, procedures and schedules for using the equipment are not changed, resulting in minimal operational impact.

A similar analysis can be performed for each of the other materials accounting subsystems. However, for the purposes of this paper, the PuO_2 powder unloading process is sufficient to illustrate the design process.

C. Evaluation

Clearly, the cost and operational impact goals have been met. However, it is apparent from Fig. 3 that a diversion would have to be quite large to be detectable. Thus, this subsystem should be modified to see if an improvement in diversion sensitivity is possible.

D. Modification and/or Iteration

One way to improve the diversion sensitivity of the PuO_2 powder unloading process is to place a small weigh hopper in series in the transfer line to the bulk storage vessel, and use the weigh hopper measurements in the material balance calculations. This is effective because weighing errors are generally proportional to the full-scale capacity of the weighing device. Thus, the new system, measurement system 2, should have a smaller material balance uncertainty.

Selection of the size of the weigh hopper is based on several tradeoffs. Reduced size reduces cost somewhat and decreases weighing errors, but there is no value in decreasing weighing errors much below other measurement errors. In addition, too small a weigh hopper will delay processing and upset normal procedures. A logical choice would be a big enough hopper to hold the contents of one canister, 8 kg of PuO_2.

E. Re-Analysis

Repeating the analysis step, with measurement system 2 above, produces the material balance and cusum charts of Fig. 4. Subsystem cost has been increased somewhat because of the added weigh hopper and its installation. Operational impact has been affected only slightly, although procedures for operating the new weigh hopper will have to be developed.

F. Re-Evaluation

Clearly, sensitivity to diversion has been greatly improved, seemingly without unmanageable increases in operational impact and cost; apparently, the iterative process has yielded a better design. The cycle could continue as desired, terminating whenever further improvement seems unlikely or too difficult.

G. Summation

At this point, the design sequence has generated a subsystem conceptual design with the following kinds of specifications:

1. The types of measurements necessary, e.g., weight;
2. The approximate range of the measurement;
3. The uncertainty desired of the measurement;
4. The procedure in making the measurement; and
5. How the measurement is to be used.

This kind of information for each of the subsystems and the system as a whole is sufficient to begin the next step, preliminary design, in which practical constraints such as physical layout and available equipment begin to be considered. If at any time during preliminary design, or even later, it becomes apparent that the performance goals cannot be reached by realizable systems, it may be desirable to return to the conceptual design step to generate a new approach.

The preliminary design step is much more detailed and extensive than conceptual design, and consequently allows a better estimate of the actual performance of the eventual system design. The expense of preliminary design requires that it be based on an intelligent application of the conceptual design principles presented here.

IV. CONCLUSION

The wide range of technologies and the intense specialization required in the design of complex safeguards systems that are coordinated with material processing make a set of formalized design and development procedures imperative. It is a fact that, too often, technical problems that bear on the overall system concept are not considered objectively; solutions are sometimes based only on immediately available expertise, or on personal preconceptions and predilections. In such cases, subsystem designs may be nearly completed before any attempt at understanding and defining the overall system requirements has been made. The subsequent combination of the relatively independent pieces then becomes the major systems engineering problem, which, as indicated earlier, may not have an adequate solution.

It is a truism that all system designs are fallible; a perfect system is unattainable, and even an optimum system is rarely achieved. System designers can only hope to use an orderly design sequence that results in a larger fraction of good decisions than can be obtained from some other piecemeal procedure.

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FIGURES

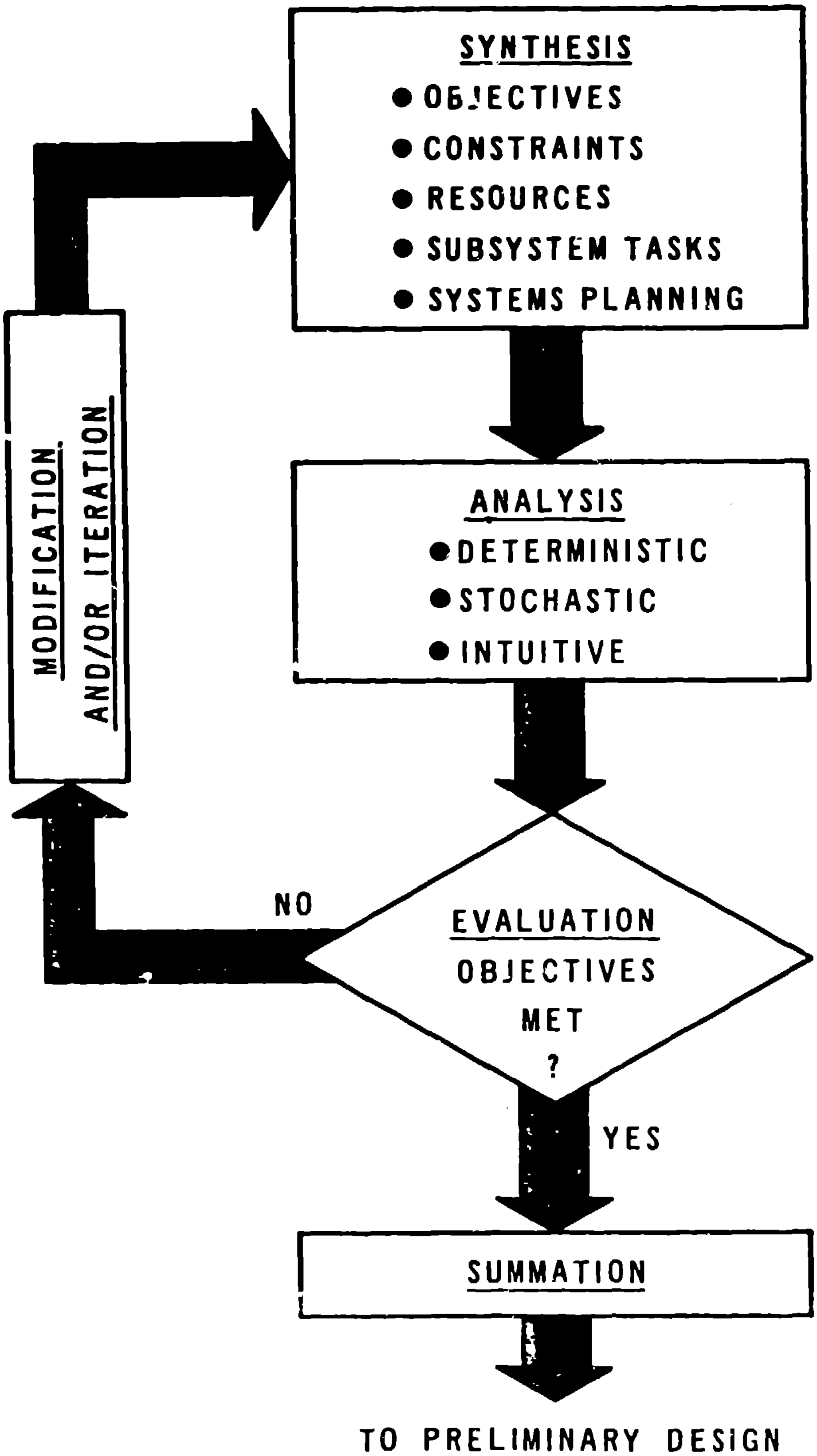
Fig. 1. Flow chart of conceptual design steps.

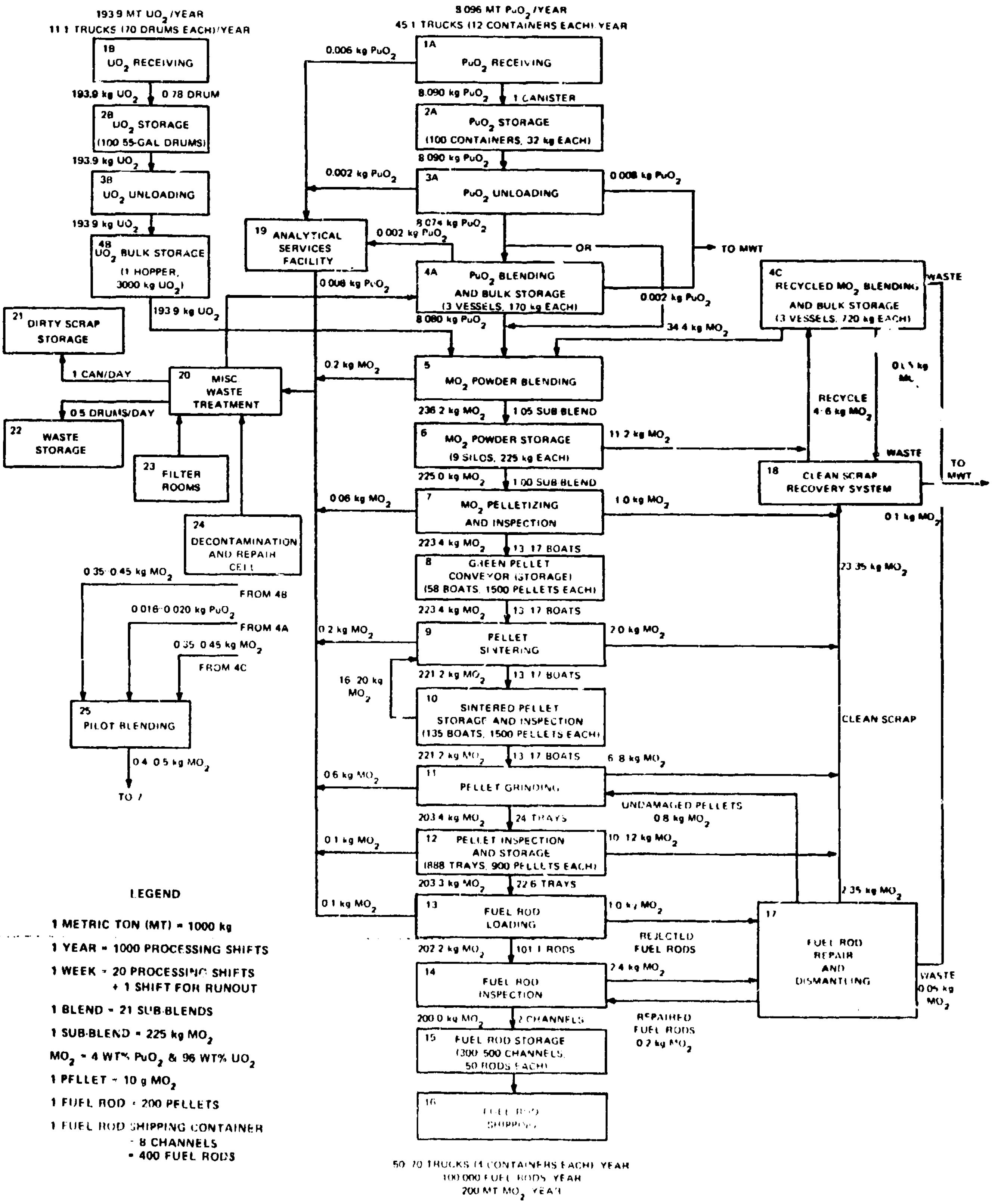
Fig. 2. MO_2 process line block diagram.

Fig. 3. Material balance and cusum data from 4 wk of typical PuO_2 powder unloading using measurement system 1.

Fig. 4. Material balance and cusum data from 4 wk of typical PuO_2 powder unloading using measurement system 2.

CONCEPTUAL DESIGN STEPS





LEGEND

1 METRIC TON (MT) = 1000 kg

1 YEAR = 1000 PROCESSING SHIFTS

1 WEEK = 20 PROCESSING SHIFTS + 1 SHIFT FOR RUNOUT

1 BLEND = 21 SUB-BLENDS

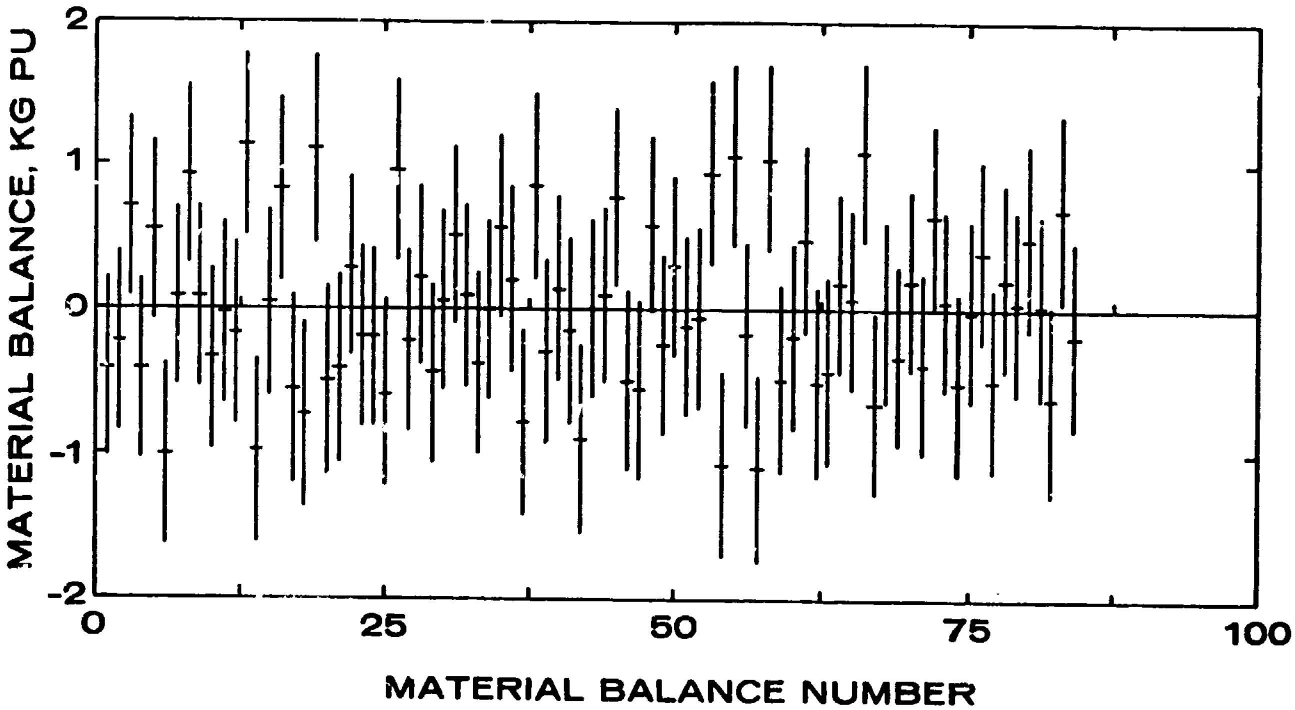
1 SUB-BLEND = 225 kg MO_2

MO_2 = 4 WT% PuO_2 & 96 WT% UO_2

1 PELLET = 10 g MO_2

1 FUEL ROD = 200 PELLETS

1 FUEL ROD SHIPPING CONTAINER = 8 CHANNELS = 400 FUEL RODS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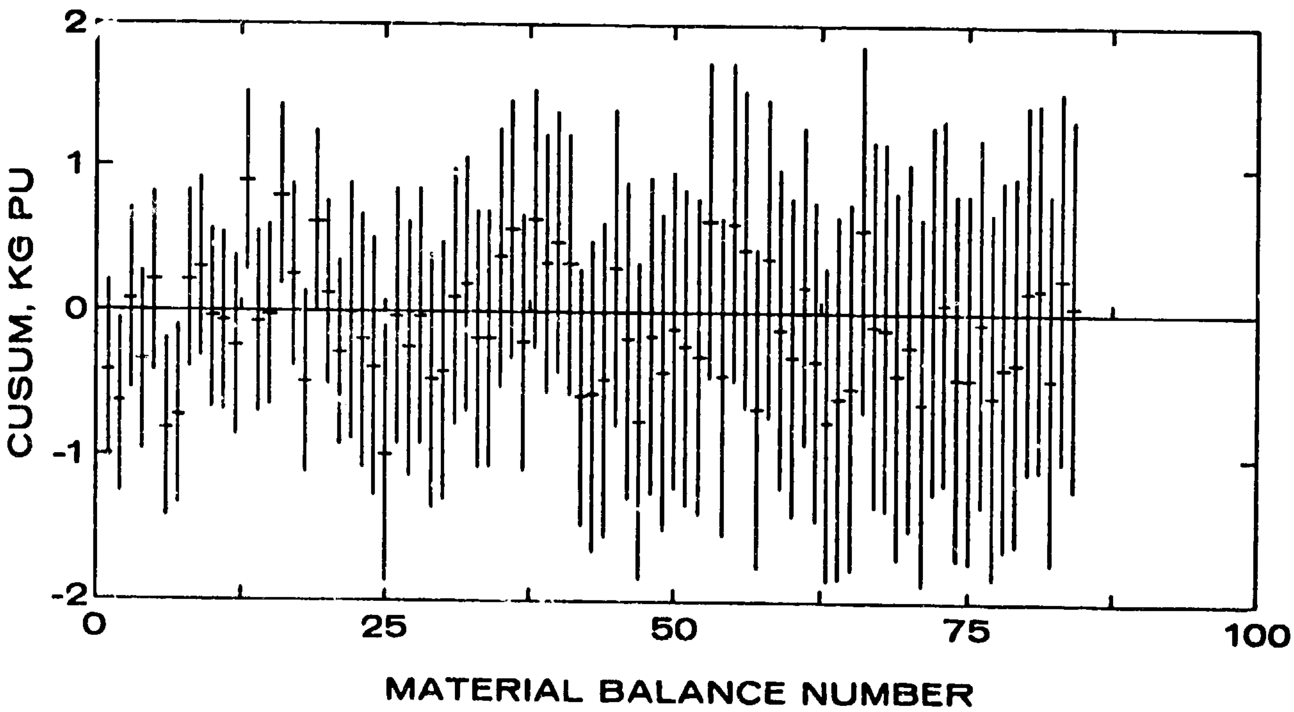
MATERIAL BALANCE NUMBER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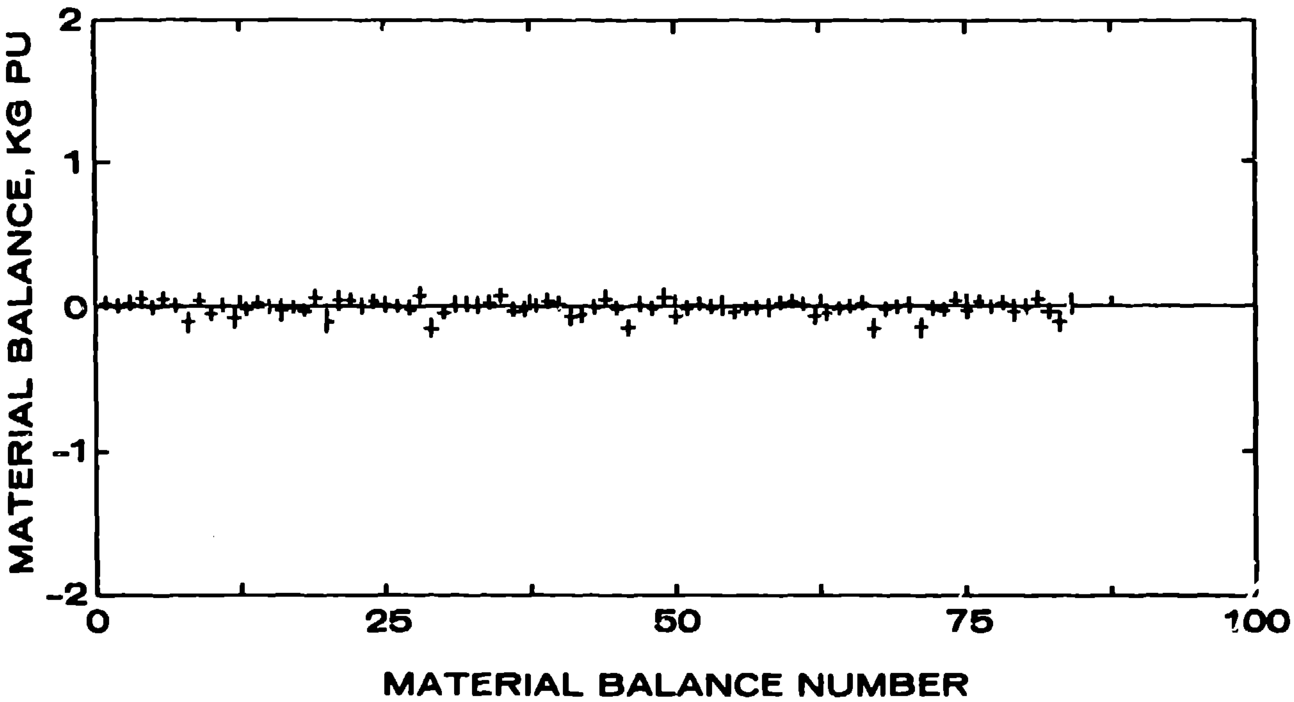

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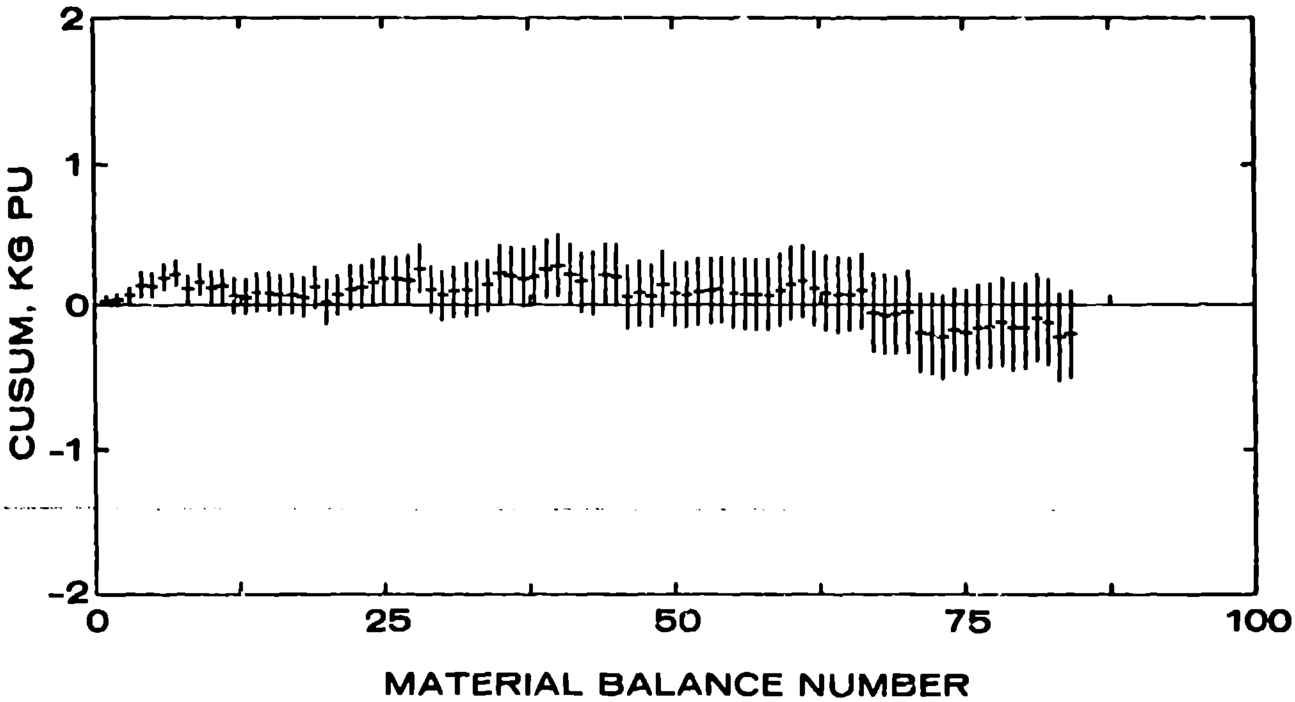

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